TRI-SERVICE GREEN GUN BARREL
(PP 1074)

Final Report
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I. Project Title

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III. Background

This final report summarizes the activities performed during the Strategic Environmental Research and Development Program's (SERDP's) PP 1074 Tri-Service Green Gun Barrel. The program's goal was to develop an environmentally friendly process for depositing wear and erosion resistant materials onto gun bores replacing the current hazardous aqueous electro-deposition process of chrome plating. Moreover, this replacement process would not have an adverse effect on the current wear life levels for the respective weapon platform. Currently, all of the defense services utilize the chrome plating process as a wear enhancer for various weapons (see figure 1). Therefore, all services will benefit from the development of a novel, non-toxic coating process. These benefits will manifest themselves through considerable expense reductions in the form of waste disposal cost savings and through compliance to government regulatory mandates. In addition, a range of materials other than chromium can be utilized with this new process.

In the past, the need for gun bore surface coatings had been dictated by system lethality requirements necessary to defeat the threat. Ammunition designers, in an effort to increase system performance requirements, have continually developed higher energy, more aggressive propellant formulations. The higher energy and hotter propellants being pursued by ammunition designers thus make coating material selection very critical for all future bore coating candidates. Uncoated gun bores exposed to these higher temperature propellants created an acute problem of barrel erosion, and did not enable acceptable barrel wear life levels to be achieved. The introduction of electro-deposited chromium provided an excellent solution at that time, since it adhered well to the substrate, was inert from chemical attack, and was well matched thermally to the substrate. Many weapon platforms, both medium and large caliber, integrated the chromium bore coating as part of their respective production cycles and reaped considerable performance benefits. At the present time, lethality requirements have again increased to a point where the chrome coating has become thermally overmatched, and the resulting wear life levels have declined to unacceptable levels (see figure 2). Other inherent drawbacks of chromium coatings are that they readily crack, providing a path for the hot propellant gases to reach the, lower melting point, substrate. This failure mode allows for the chrome coating to be removed from the steel substrate, thus allowing for excessive wear and erosion. Furthermore, the toxic nature and exorbitant disposal costs of hexavalent chromium demand the attention for a new clean process.

IV. Objective

The objective of this effort was to develop an innovative dry (non-aqueous) process for the deposition of chromium or other materials equally suited for the bore protection of a gun barrel to replace the aqueous electro-deposition process. This novel non-polluting process is called the Cylindrical Magnetron Sputtering (CMS) process (see figure 3). CMS is a magnetically enhanced sputtering system that is capable of providing high deposition rates over large areas while maintaining low substrate heating levels. The project advanced the necessary applied research and developed the appropriate technological inputs, which culminated in an advanced technology demonstration addressing specific performance requirements in the coating of medium caliber barrels. This project also served as a technology feeder program for large caliber barrel applications as an integrated solution to the current barrel manufacturing process (see figure 4). There exist several other attractive benefits that can be derived from the use of CMS as it pertains to minimizing the impact on the gun tube manufacturing process. Benet Laboratories preferred CMS as the coating process for this effort for a number of reasons:

1. It does not generate excessive temperatures during processing, therefore not producing heat affected zone (HAZ) in the gun steel and affecting fatigue life.
2. It protects all residual stresses present at the bore surface in the gun steel of autofrettaged gun barrels.
3. It allows for the deposition of a large range of refractory materials, other than but not excluding, chromium.
4. It is a very attractive plug-in solution to the existing gun barrel manufacturing sequence.
5. Deposition rates are acceptable and post-processing of a PVD coating (i.e., honing) is unnecessary.
6. It is environmentally friendly, which makes it very attractive from a regulatory perspective.

Finally, the CMS process can be reversed to remove coating, if necessary. The relevancy of this coating technology is not limited to just gun tubes. Sputtering is a highly flexible process, which can be adapted to many applications. Other areas with possible application include recoil mechanism cylinders, aircraft landing gear, and oil processing, power generation, and mining exploration industries.

There was tri-service support (Army, Navy, Air Force) for the program, as well as Environmental Protection Agency involvement. This program was also heavily leveraged with other programs with concerns from not only the environmental area, but also from a gun barrel wear performance perspective. These leveraged programs include: Future Tank Main Armament (FTMA), Environmental Quality Basic Research and Development (EQBRD), Sustainable Green Manufacturing (SGM), and Strategic Technology Objective (STO). Private industry producers of the medium caliber barrels (Alliant Tech Systems, General Dynamics Armament Systems) have expressed interest in the environmental cost benefits of CMS and have offered their continued support of the overall program.

V. Technical Approach

In 1997 a peer review board of the Army's top technical experts was assembled to determine what would be the lead approach to rectify the current problems with gun barrel coatings. Based on the technical accomplishments at that time and the live firing data collected, the barrel coatings deposition process CMS was chosen as the lead approach to 1) replace the toxic chrome plating process, and 2) extend the barrel life by introducing a superior wear and erosion mitigating material; namely tantalum (Ta). Ta is a highly refractory material (melting point 1130°C higher than chromium) and has a relatively low thermal conductivity (34 W/m°C less than chromium at 20°C). The derived requirement to select coating materials with acceptable melting points is essential. Ta is also more resistant to corrosive propellant by-products than high contractile (HC) chromium, and alpha phase Ta (Ta can be nucleated in two distinct phases: alpha and beta) is more ductile than chromium. This ductility is a very attractive characteristic of Ta since it will resist thermal shock and cracking better than HC chromium.

The overall technical approach was determined at the outset of the program. A thorough investigation of the physical vapor deposition process as it relates to CMS was conducted. Extensive reviews of current and previous related work were performed. This included literature searches as well as recent planar, and triode sputtered efforts performed by Benet. At the same time, a CMS coating demonstrator was being developed. Most sputtering systems are, to some extent, custom made (see figure 5). This coating demonstrator had the flexibility to accommodate gun tube sections with bore diameters ranging from Ø25-mm to Ø120-mm, and full size gun barrels with bore diameters ranging from Ø25-mm to Ø45-mm. Initially, test specimens were coated to determine principle process parameters such as inert gas sputtering pressure levels, substrate temperatures, inert gas flow rates, and substrate / target cleaning requirements. Every coated test specimen was characterized through a standardized battery of laboratory tests, which comprise the Benet Laboratories' Coating Protocol (see figure 6). This protocol was devised to examine, on a consistent basis, the coating's adhesion, thickness, hardness, phase, morphology, density, thermal shock characteristics, interfacial properties, texture, and purity. At the conclusion of the protocol, after a number of reports were generated, a coating experts' review was conducted. The information and insights gained from the characterization of each coating specimen was used to adjust process parameters for subsequent coating runs. Program milestones required full size barrels to be coated and then fired to ascertain the coating's performance. Post-firing characterization protocol activities were conducted to gain as much understanding as to why a coating performed or did not perform well. The modeling efforts conducted in parallel by the various leveraged programs also provided invaluable process related information that was utilized at various junctures of the program (see figure 7).

The initial approach was to coat 25-mm test hardware in the form of first specimens, then tube sections, and finally full size barrels. A program with Tri-Service support was laid out based on coating and firing M242 Bushmaster and GAU-12 platforms, respectively. During the third year of the program, it was determined that the physical constraints imposed by the space-limited 25-mm bore diameter, as it directly affected the CMS approach being pursued, were too great to overcome within the remaining program time frame. These technical challenges presented by the 25-mm geometry as it pertains to the CMS process are not insurmountable, but would have required additional time and resources. With the approval of the SERDP office, a shift to more

"dimensionally friendly" 45-mm diameter hardware was made. Therefore, the original proposal plan was no longer applicable, and will not be summarized here.

It should be noted that the final goal of this undertaking remained developing a process for application of alpha phase Ta directly to gun steel using CMS techniques. The resulting performance of the coating would still be determined through firing tests and performance-related criteria.

VI. Summary

The final products for this program consisted of a total of two 45-mm gun barrels, which were coated and delivered on-schedule for live firing test. All hardware testing was performed under the auspices of the leveraged Future Tank Main Armament (FTMA) program. The aim was to demonstrate state-of-the-art designs and manufacturing processes for barrel coatings consistent with the physical requirements, interior ballistic design, and performance parameters established for the FTMA. The firing platform utilized for testing was the smooth bore French CASIUS 45-mm (see figure 8). This gun tube is designed and the ballistic cycle is matched to simulate (from the coatings perspective) the same thermal and mechanical stresses experienced in the 120-mm gun over the first meter of travel (see figure 9). Further, the very chemically aggressive, unablated German designed L1-M propellant (isochoric flame temperature 3650 °K) was utilized for all firings (see figure 10). Accordingly, any coating (material, process) that could withstand the environment produced in CASIUS would be an excellent candidate for future medium or large caliber coating development.

SN 35305: Interim Deliverable – Spring 2001

The first barrel (SN 35305) was coated and fired in June 2001, and this deliverable was regarded as a developmental trial. The interim test firing results for tube SN35305 were very encouraging. A total of (20) 45-mm slug rounds were fired through the CASIUS 120-mm wear simulator. This interim test was significant for two reasons: 1) it provided an unavoidable performance related milestone (reality check) to verify overall maturation level for the CMS process development, 2) it provided an opportunity to assess, alter, and determine the optimum path forward for the CMS process in preparation for the final test the following spring. Although the coating adhesion criteria established in the FTMA test plan had not been exceeded after (20) rounds, the test was voluntarily stopped. It was clear that the coating was slowly degrading in certain areas, and ending the test would preserve failure modes, thus allowing for more meaningful coating characterization data. The (20) rounds fired represented a 100% improvement over CMS coated CASIUS hardware fired in 1997 (under a separately funded program).

A tantalum coating with a 10-micron niobium interlayer was utilized for this tube. The niobium (Nb) interlayer was introduced for a number of reasons: 1) Ta has two phases: an alpha phase and a beta phase; at this juncture of the program, nucleating alpha-Ta onto gun steel was not yielding satisfactory results and required further work, 2) Nb has only one phase and CMS coated specimens to date using Nb had yielded very dense structures, 3) its (Nb) adherence to

gun steel was acceptable, 4) an interlayer of Nb would ensure the topcoat of Ta to be 100% alpha-Ta, 5) Nb and Ta are similar materials and therefore adhere to each other well.

One contributing cause of the adhesive losses experienced in SN35305 can be attributed to an undersized condition that was caused by excess coating material being deposited in an area that extended from the origin of the tube to approximately the 18 inches in overall bore travel. This undersized condition caused more interference between the projectile sealing band and the coating, increasing the shear stress within the coating to levels that would create dislodging of the coating from the substrate. This interference even prevented the first round from chambering properly. The over-coating condition was caused by an over ionization of the plasma, which resulted in more coating being deposited than expected. This out-of-tolerance situation was apparent after final inspection of the coated hardware. Any rework (e.g. honing) of the coating prior to shipment would have presented a high risk and also would have significantly delayed the firing schedule, and therefore was not an option.

Another area of concern for tube SN35305 was the presence of high oxygen concentrations in the pre-fired coating (verification ring cut from the muzzle end). The highest concentrations were observed at the coating interfaces. Oxygen contamination at the interface of the coating will promote poor adhesion. This oxygen contamination was due to the presence of air and moisture caused from opening the system during the pre-deposition cleaning process (removal of contaminant collection shields) and the Nb interlayer deposition phase (change to Ta target). It must be also noted that a high oxygen concentration in the coating will render the coating less ductile and more susceptible to adhesive failure from shear loads.

Areas in the tube, which were within dimensional specifications, performed well from an adhesion perspective. Cracking of the coating was observed in these areas and can be attributed to the fact that oxygen contamination in the coating will result in increased susceptibility to thermal shock and subsequent cracking. Figure 11 summarizes the results. The post forensic observations resulting from the characterization of SN35305 generated a list of corrective actions with regard to the overall process. These corrective actions had varying risks associated with them, and were implemented over the next year in preparation for processing the final gun tube.

SN 35302: Final Deliverable – Spring 2002

The second barrel SN35302 was coated and fired in May 2002, and was the final deliverable for the program. The overall results continued to show steady and significant improvement regarding coating performance and CMS process integrity. A total of (30) 45-mm slug rounds were fired through the CASIUS 120-mm wear simulator. The process applied to this tube can be best summarized as the culmination of a number of process modifications implemented and successfully realized based on lessons learned from the 2001 test. Specifically, a first time utilization of an improved cleaning process was implemented, which did not require the vacuum system to be opened after final plasma cleaning, and prior to commencement of coating deposition. Further, a modification to the target’s magnetic field performance was realized in this process, so as to ensure the bore coating deposition levels were consistent and in-tolerance

over the entire length of travel. These firing results represent a 50% increase over the performance levels recorded in 2001.

Tube SN35302 was coated with only Ta. Test cylinders produced during process development activities indicated a 100% alpha-Ta coating was indeed possible, but getting these results on a consistent basis proved to be elusive. SN35302 can be characterized as a mixture of the two phases. Large patches of beta-Ta were observed along certain segments of the tube separated by smaller alpha-Ta patches. All of the alpha-Ta patches were located in zones 1, 2, 3 of the barrel. The muzzle end of the barrel (zones 3, 4, 5) was predominantly beta-Ta.

A muzzle end verification ring was cut from the finished tube prior to shipment. The coating in this ring was 100% beta-Ta, and exhibited hardness levels (important for generating shear stress at the interface to test adhesion) similar to high contractile (HC) chromium. {Note: An explanation for why the muzzle end area of this tube was predominantly beta-Ta was due to vacuum system limitations. The vacuum end seals had to be kept cooler (175°C) during processing than the rest of the tube (200°C)}. A series of protocol tests were performed on this muzzle ring, which included the adhesion protocol mechanical groove test. The results of this groove test demonstrated adhesive levels in the coating (especially at the 3:00 position) on an equal par with groove test results observed in production HC chromium (see figure 12). These results were very significant, clearly the best of any CMS coatings to date, and can be attributed to the new cleaning process developed especially for this CMS coating application. The adhesion of the coating at this location was equally exceptional after the firing test. The exceptional adhesion exhibited in the muzzle ring was observed to vary greatly throughout the length of the tube.

The coating in this tube failed in two modes: 1) adhesive failure mostly observed in zones 1, 2, 3 toward the origin, and 2) cohesive failure in thin radial strips observed towards the muzzle in zones 3, 4, 5. This firing test was stopped at 30 rounds due to excessive adhesive coating losses in zone 1 closest to the origin (0 to 200-mm of travel from origin) where more than 50% of the coating had adhesively failed. Zone 1 was also where there was evidence of the slug round balloting against the bore wall, which may have mechanically removed coating. The highest heat inputs for the 45-mm (L1-M propellant) ballistic cycle were in the zone 2 region of the tube (200 to 400-mm from the origin). This was also the region where a large area of virgin alpha-Ta was deposited and well adhered. This alpha-Ta region was comprised of some of the thickest coating deposited in the tube. After 30 rounds had been fired, this alpha-Ta coating performed exceptionally well by protecting the substrate and preventing the formation of a heat-affected zone (see figure 13). As figure 13 shows, no HAZ formed under the Ta coating. The adhered patches of alpha-Ta did exhibit heat check cracking in a rectangular (mudflat) pattern. The crack density of the Ta coating for SN35302 was significantly less (see figure 14) than crack density levels seen in production chromium coatings (macro-cracks ~ 8 cracks/mm, micro-cracks ~20cracks/mm) after firing. These outcomes were very noteworthy and verify the overall coating performance and process objectives of this program.

Annual reports for this program dated December 31, 2001, December 31, 2000, December 31, 1999, and March 1, 1999 have been submitted to the SERDP office for this program.

VII. Project Accomplishments

For the two-year period starting in mid-calendar year 2000 and running through mid- calendar year 2002, a number of CMS process related breakthroughs were experienced for this SERDP effort. In addition to the gun barrels, over twenty cylindrical specimens were coated and evaluated from September 2000 through April 2002, in support of developing a viable CMS process. The overall aim was to develop a reliable coating process which would produce high quality coating specimens with excellent adhesion. By the end of the two-year period, many of the goals regarding CMS coating quality had been achieved. The desire to deposit, on a consistent basis, highly dense "zone T" (see Thorton diagram, figure 15) coatings had become a reality. Other important process related areas addressed during this time were plasma generation and manipulation techniques, and pre-cleaning procedures. Excellent results were derived with regard to the former area, while more investigation and refinement is required for the latter area. From the outset, the overriding roadmap for tracking the overall CMS process development took the form of eight coating performance metrics with which each cylindrical specimen was compared after characterization was complete.

1) <u>Zone T Morphology (per Thornton)</u> – The achievement of this metric was mainly a function of sputtering pressure, temperature, and surface impurity levels. As lower processing pressures began to be attained through modifications to the vacuum system and plasma generation techniques, pressures in the range of 1 – 10 mTorr were realized. Thus, the coating morphology became denser, less columnar, and more cohesive. Increasing temperature levels also had an impact on the morphology of the coating. The 45-mm CASIUS gun tube was an autofrettaged pressure vessel. The autofrettage technique provides added strength to the gun, but does set an upper limit to coating deposition process temperatures. As a result, any coating deposition process temperature greater than 250°C could reduce the overall strength of the gun. In addition, the vacuum system design utilized during this effort had seal integrity issues at higher temperatures. For these reasons, the substrate temperature levels for the majority of the CMS specimens produced were controlled to range from 175°C to 250°C. Therefore, there remains considerable upside (especially if the gun barrel is not autofrettaged, and metallic vacuum seals are utilized) for increasing substrate temperature with regard to moving from "zone T" to a denser "zone 2" coating morphology. Additionally, processing at higher temperatures greatly increases diffusion of the coating material to the substrate and thus improves overall adhesion. Finally, an impact on coating morphology was also realized once vacuum base pressures approached 1x10-8 mT, which effectively minimized the presence of contaminants such as water vapor.

2) <u>100% Alpha Phase</u> – The nucleation of a 100% alpha-Ta coating on a cylindrical steel substrate was achieved, but was difficult to repeat on a consistent basis (see figure 16). There were a number of parameters that affected whether alpha-Ta was nucleated versus beta-Ta. Time limitations did not allow for an in-depth examination of each of these parameters. Temperature, sputtering gas, sputtering gas pressure, surface impurity levels, the deposition rate of Ta onto the substrate, and the level of contaminants in the vacuum chamber were all believed to factor into whether alpha-Ta or beta-Ta was nucleated. In the case where alpha-Ta was produced, a 300°C temperature level in the middle of the

31-inch long test specimen was maintained. The fact that 100% alpha-Ta was achieved without utilizing pulse sputtering or bias sputtering was quite extraordinary. The sputtering gas used was Krypton and an average sputtering gas pressure of 10 mT was employed.

3) Hardness - The hardness of the alpha-Ta produced in the coated test specimens ranged on average from 200-300 Knoop. This represents a higher hardness than normally found in bulk alpha-Ta, which has a typical hardness of 100-200 Knoop. This hardness level was a desired outcome, and was viewed as a performance benefit making the CMS alpha-Ta: 1) more resistant to mechanical wear, 2) more ductile than electro-deposited HC chromium (800-1000 Knoop) and thus more resistant to thermal shock, and 3) an overall better coating candidate for gun tube applications. The typical hardness of the CMS beta-Ta produced ranged from 900 –1100 Knoop (see figure 17).

4) Acceptable Adhesion/Cohesion – The adhesion of the bore coating with the underlying steel substrate has been shown to be and remains critical to barrel wear life. Regardless of the materials and processes applied to coat the gun tube bore, an acceptable level of adhesion must be maintained. Throughout this program, the adhesive properties of production chromium to gun steel was used as a baseline to define acceptable adhesion and to track the progress of CMS coating adhesion (see figure 18). It was clear after firing SN35305, that adhesion of the coating to the substrate would be a major focus in preparation for SN35302. The key to adhesion was the plasma cleaning process, which provided an atomically clean substrate free of contaminants and oxides prior to sputtering. With regard to the present cleaning process, the vacuum system had to be opened prior to initial deposition in order to remove contaminant collection shields used during the cleaning process. Eliminating this final vacuum system-opening step became a priority. Further, after studying the process and observing the adhesive behavior of numerous coated specimens, an inherent weakness in the plasma cleaning process used for SN35305 was discovered.

   Part of the coatings protocol requires rings to be cut from various axial locations of the coated test cylinder. The 12:00 position during plating is referenced and four specimens are cut at 90° from each other. The adhesion groove test was then applied to each specimen. When the four sectors were compared, the adhesion was always better in one location and always progressively worse as one approached the sector 180° opposite the best location. A closer look at the coating/substrate interface detected a re-deposited iron layer present at the interface (see figure 19). This layer had a major impact on the coatings adhesion and was always greatest in one area of the ring (see figure 20). The scientific reasons for this were traced to the generation of non-concentric plasma due to the magnetic field utilized during cleaning which imparted a highly non-uniform vapor flux to the cleaning process. The acknowledgement of this problem, as it applied to the deposition process and plating circumferentially symmetric coating distributions, had been the driving force in redesigning the target configuration prior to coating SN35305. The major impact of this magnetic flux inconsistency was not believed to be critical from a plasma cleaning perspective until this juncture of the program. In addition, the collection shield used during substrate plasma cleaning was smaller in diameter than the

substrate, and therefore, was not able to collect all of the surface contaminants (see figure 21). The technical challenge was to fabricate a substrate-cleaning device that would: 1) allow itself to be stowed inside of the vacuum system, 2) generate a concentric magnetic field and predictable plasma for cleaning, and 3) guarantee all contaminants were collected. This was an extremely ambitious scientific and technical undertaking within the confines of the program schedule. A cleaning device (see figure 22) previously designed for large caliber applications was modified, built, and tested (under extreme duress) just prior to when tube SN35302 had to be coated. The outputs of this effort were shown when the adhesive performance of the verification muzzle ring cut from SN35302 indicated the beta-Ta coating adhesion was on a par with chromium. The improved adhesion throughout SN35302 (especially in zones 1, 2, and 3) as compared to SN35305 is evidence of progress in this area.

The cohesive properties of a coating have also been shown to be critical to barrel wear life. Cohesiveness is a measure of how substantial (dense) a coating is and thus how well it will survive the repeated mechanical cycling of rounds being fired through the gun tube. Poor cohesion characteristics in a coating lead to a reduction in the coating thickness and a subsequent change in the thermal properties of the coating as it relates to the steel substrate. The coating density will determine how well it performs from a cohesive standpoint. Therefore, improving the overall bulk CMS coating morphology dominated process development activities until SN35305 was coated and fired. The overall cohesion of the coating in SN35305 was excellent mainly due to the fact that the coating was alpha-Ta. In SN35302, there were areas of cohesive failure observed in zones 3, 4, and 5, which can be directly attributed to the presence of brittle beta-Ta in these regions.

5) Coating Over Full Length of Sample – In the early stages of the development of the CMS process, sustaining plasma along the entire length of the cylindrical specimen proved to be a challenge. The plasma would be present in some segments of the test cylinder, but extinguish itself or act unstable in other areas. In many cases, this was due to the electrons reaching the anode before a sufficient number of ionizing collisions could take place. Regulating and modifying specific parameters such as gas pressure gradient, cathode to anode voltage, target current density, cathode to anode distance, and cathode to substrate distance corrected any problems encountered. The length to gap ratio is also considered a basic parameter with regard to coating over the full length of the sample. It must be noted that within the time constraints imposed on this program, the chamber regions of both gun barrels were not specifically addressed for the coating process. Plasma generation techniques were specifically developed for deposition and cleaning of the gun tube bore only. The chamber section geometry would have been addressed if time had allowed and would not have presented a technical challenge.

6) Even Distribution Over Length – The coating of interim deliverable SN35305 proved coating the entire length of the 54-inch test sample was attainable. Conversely, it also proved that maintaining established bore tolerances with the newly modified target design, which was utilized for this deposition, required further study. A situation occurred during the processing of SN35305 which created an over ionization of the

plasma and resulted in a heavy deposition of material in the first 18 inches of travel. This is not a desired outcome since the extra coating interferes with the passage of the projectile creating a higher probability of shear induced adhesive failure at the coating interface. A Flux-2D parametric study was conducted using current density, plasma power voltage, and magnet spacing to analyze the target design and ensure predictable and controllable plasma would be generated for the selected deposition rate during processing of tube SN35302. This study also had to account for target oscillatory motion during processing. This effort was a success as the coating distribution for SN35302 met the tolerance specification throughout the bore (see figure 23).

7) Even Distribution Around Inner Diameter – During the early phases of the program, the variability of the coating thickness around the circumference at any axial location was extremely unpredictable. This was due to the magnetic field generated by the centerline current target design being employed at that time. Prior to the coating of SN35305, the target configuration was redesigned. The plasma non-concentricity situation immediately ceased to be a problem (see figure 24).

8) Chrome Equivalent Deposition Rate (.001 in/hr)- The goal of depositing CMS coatings at 25 microns/hour (.001in/hr) was based on meeting or exceeding the standard deposition rate for electro-deposited chromium. Depositing Ta at 25 microns/hour was successfully demonstrated on one of the cylindrical test specimens produced during the program. Otherwise, the majority of the specimens were processed at deposition rates of 10 to 12.5 microns/hour. Slower deposition rates (6 microns/ hour) were found to allow for more oxygen to enter the coating surface. Yield rate is a function of the ion energy, the cathode material, as well as the ion mass of the gas. The choice of process gas was observed to have an impact on film growth rate. Utilizing a heavier gas ion and raising, if necessary, the current ion densities were shown to increase the sputtering rate. Increasing ion energies alone did not guarantee a sputtering yield increase. It was also shown that yields vary more with ion species (gas type) selected, than with target species (material) selected. Argon, krypton, and xenon were all used to coat cylindrical specimens. Krypton was the gas of choice used to coat both gun barrels. Both tubes SN35305 and SN35302 were coated at deposition rates of 12.5 microns/hour since deposition rates were not to take precedence over adhesion and integrity of the coating.

VIII. Conclusions

In summary, this SERDP funded program provided for the development of a CMS coating process, which culminated in the test firing of two CMS coated barrels. The process used for the finished hardware reflected a level of technical risk that was, although significantly reduced, higher than what would have been otherwise desired to guarantee success. This situation was a product of a slow program start (1998-1999), which resulted in an aggressive time schedule for hardware completion. The difficulties encountered during this risk reduction phase with regard to developing a reliable CMS gun bore coating process were technically challenging, but certainly surmountable. This is supported by the fact there were many significant CMS process-related advancements and steady improvements throughout the process development phase. Two major improvements were overall quality of the bulk coating and the development of plasma generation

and manipulation techniques. These scientific lessons learned will be invaluable to future advanced coating efforts using CMS applications.

However, based on the results of the tests, the major obstacle for the PVD process at this time remains adhesion. The percentage of coating that adhered to the steel substrate was unacceptable. Inadequate cleaning of the substrate prior to coating and process related deficiencies during coating were the causes of these adhesion-related losses. Both of these problem areas can be corrected. In the areas where the coating did adhere perfectly and had adequate thickness, the performance of the coating was excellent. In these areas, a heat-affected zone (HAZ) was absent after (30) rounds, and the crack density was considerably less when compared to chromium coatings. If more consistent coating adhesion to the substrate can be attained throughout the length of the bore and chamber, it can be surmised from these test results that a solution to the wear and erosion problem is attainable using CMS techniques.

When compared to other potential coating processes, CMS does not affect barrel fatigue life. CMS is a low temperature process, and therefore, does not produce a HAZ during processing, which also has a negative effect on fatigue life. Further, CMS does not affect autofrettage stresses at the gun bore surface. Finally, the refractory materials deposited using CMS have demonstrated a lower propensity for cracking when compared to chromium, which will extend the barrel wear life.

Executive Order 13148 mandates the U.S. military reduce the level of toxic wastes from all current manufacturing processes by 2006. Because CMS is an environmentally clean process, its implementation into the large caliber gun barrel production process will satisfy this regulation. In addition, the toxic waste disposal costs associated with the chromium process will be eliminated. The elimination of these disposal costs will reduce existing production costs by millions of dollars per year depending on the production rate. These toxic waste costs are projected to continue to rise, which makes the environmental impact of switching to the PVD process more significant over time.

IX. Transition Plan

Implementing the PVD process into full-scale production is low to medium risk. This effort is being planned and implemented at Watervliet Arsenal for coating the bore surface of large caliber cannon barrels. The first full-scale gun barrel deposition, utilizing CMS processes, is scheduled for 2004.

The CMS coating process is a plug-in replacement process for the existing gun barrel production manufacturing process (using chromium). Unlike chromium, CMS requires no surface finish post-processing activities.

The production rate for US made 120-mm tank guns has not been forthcoming for recent years. This fact makes estimating a cost comparison for chrome versus PVD coated barrels very difficult. In qualitative terms, the labor and capital costs for PVD should be slightly less than those costs for chromium. Furthermore, the facilities, tooling, and process development costs for PVD method should be comparable to chromium plating method. Finally, the environmental

cost reductions associated with the PVD process should reflect cost savings of approximately 10 percent per barrel

X. Recommendations

Clearly, from the results of this program as well as the extensive work Benet, and others, have done prior to this program, support of this technology should continue through its inception into the large caliber gun barrel production process. Though the particular variant of sputtering that this program pursued (CMS-IM, Internally Magnetized) did not accommodate the Cr replacement needs of smaller bore guns (under 40mm), other variants of the cylindrical magnetron sputtering process have shown great promise for the smaller barrels. In particular, CMS-EM (Externally Magnetized) removes the space requirement that the CMS-IM (Benet process) utilized. By generating the magnetic field external of the gun barrel, more room is available for plasma generation within the smaller medium caliber barrels under 40mm. Though time and funding did not allow Benet to pursue this alternative CMS variant, other companies have with initial success.

The need to replace chromium on medium and small caliber barrels is extremely important since over 40,000 chrome plated, medium caliber barrels are currently scheduled for production through 2013. This does not include the thousands of M2HB 50 cal barrels produced each year. Included in the list are all the Bushmaster variants (M242, Mk44, etc), all the Vulcan variants (20mm M61 series), and the 50 caliber weapons. As compared to the relatively low large caliber barrel production, SERDP can realize a much higher payoff by supporting future initiatives to replace chromium from medium caliber barrels.

XI. Appendix A

1. Texture, Structure, and Phase Transformation in Beta Tantalum Coatings", S.L. Lee, P. Cote, M. Cipollo, presentation, Metallurgical Coatings and Thin Films, (2003).
2. Nondestructive in-Situ XRD Monitoring of Crystalline Growth in Sputtered metal and Alloy Films", S.L. Lee, J. Mueller, American Society for Nondestructive Testing Spring Conf and 12th Annual Research Symposium, (2003) 28-29.
3. "Application of Laser Pulse Heating to Simulate Thermo-Mechanical Damage at Gun Bore Surfaces", P. Cote, S.L. Lee, M. Todaro, G. Kendall, Gun Tubes and ASME Journal of Pressure Vessel, submitted (2003).
4. "Application of Laser Pulsed Heating to Simulate Thermo-mechanical Damage at Gun Bore Surfaces", P. Cote, Sabrina Lee, Mark Todaro, Gay Kendall, US Army Tech Report, ARCCB-TR-03002 (2003).
5. "In-Situ Phase Evolution Study in Magnetron Sputtered Tantalum Thin Films", S. L. Lee, D. Windover, T.M. Lu, M. Audino, Thin Solid Films 420-421, (2002) 287-294.
6. "High-Rate Sputter-Deposited Tantalum Coatings on Steel for Wear and Erosion", S.L. Lee, D. Windover, M. Audino, D.W. Matson, E.D. McClanahan, Surface and Coatings Technology 149 (2002) 62-69.

7. “In-Situ Phase Evolution Analysis of Sputter Deposited Tantalum Thin Films”, US Army Tech Report, ARCCB-TR-02014, 2002.

XII. Appendix B

Figure 1

PRIMARY BENEFICIARIES OF THE TECHNOLOGY

ITEM
USAF/USN M61A1 “Vulcan” (20mm) Aircraft Cannon
US ARMY M242 (25mm) “Bushmaster” Chain Gun
USN CIWS “Phalanx” (20mm) Air Defense Cannon
US ARMY / USMC (20mm & 25mm) Helicopter Cannon
USAF GAU-8 (30mm) Aircraft Cannon
USMC AV/8B (20mm & 25mm) Aircraft Cannon
USN 5"/54 Gun
USN “Firebox” Multi barrel Launcher
USMC .50 Caliber Machine Gun
US ARMY Main Armament Systems (120mm Cannon)
US ARMY Artillery Systems (155mm Cannons)

Figure 2

ABRAMS

Barrel Condemnation

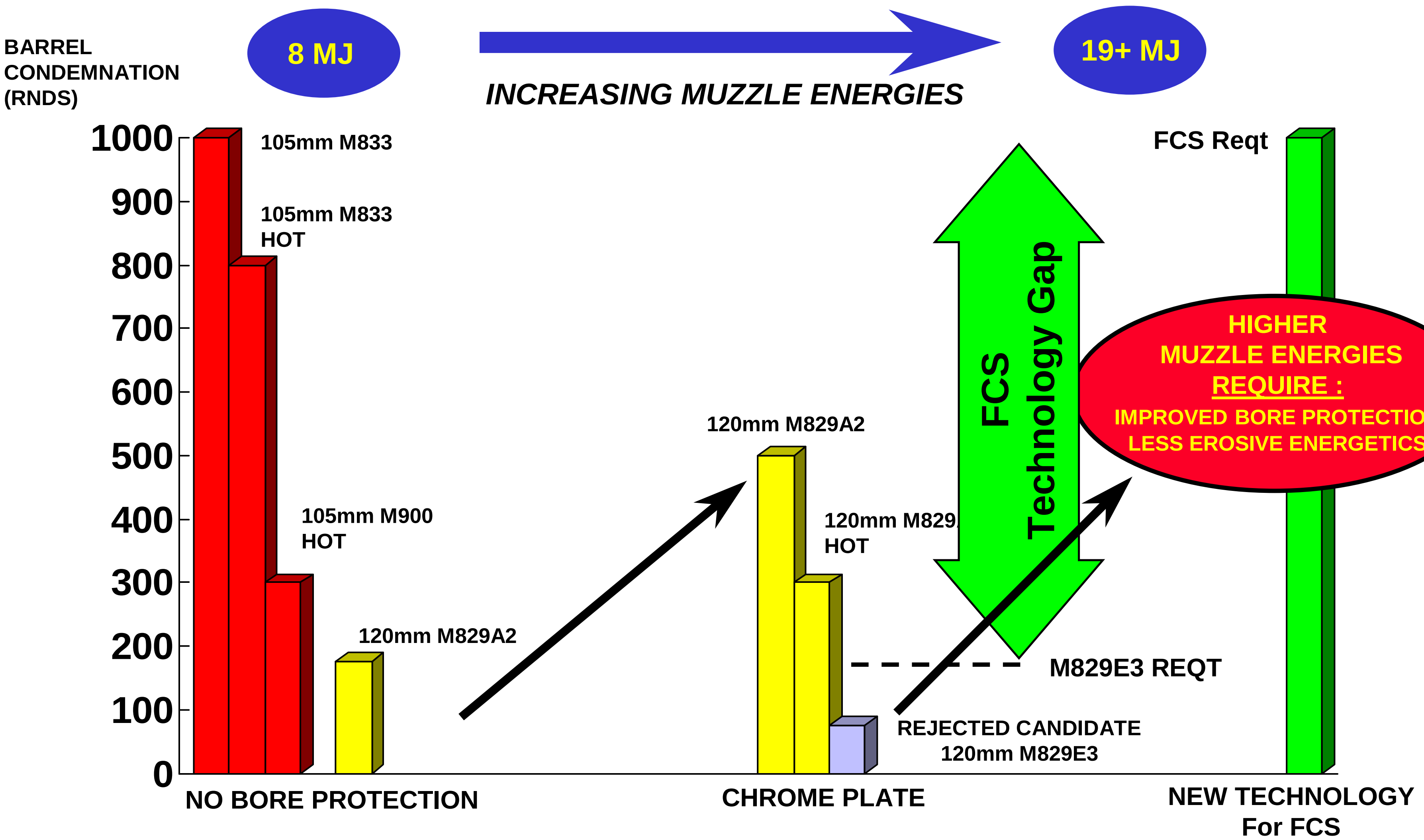
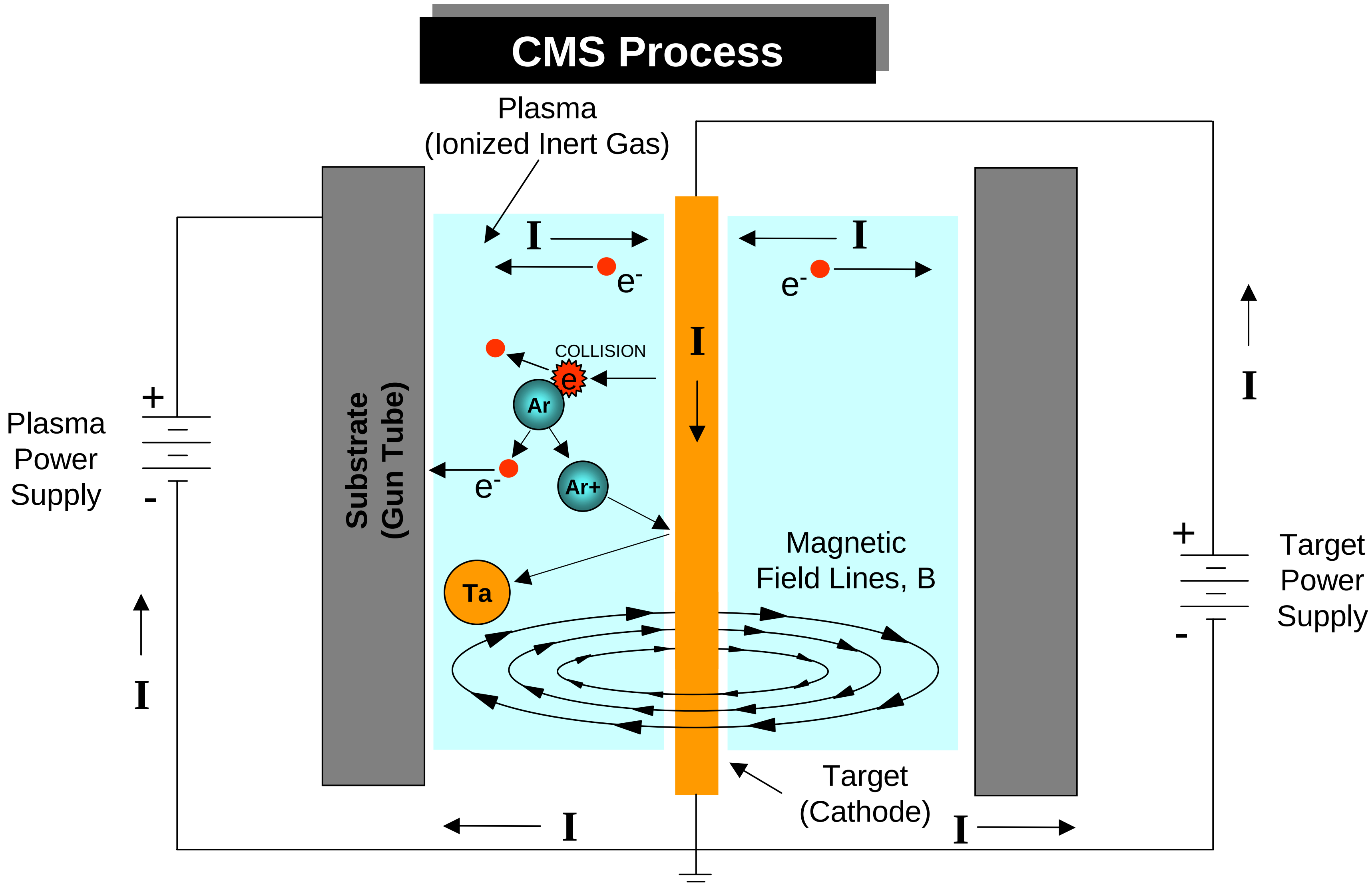


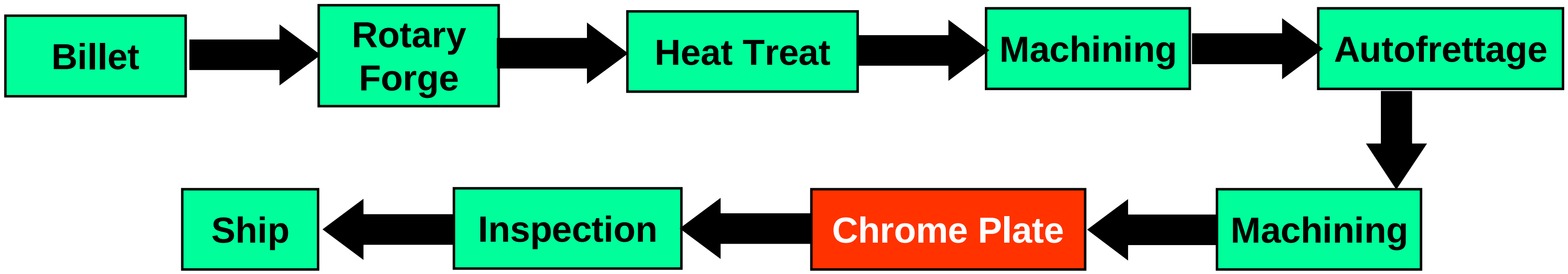
Figure 3

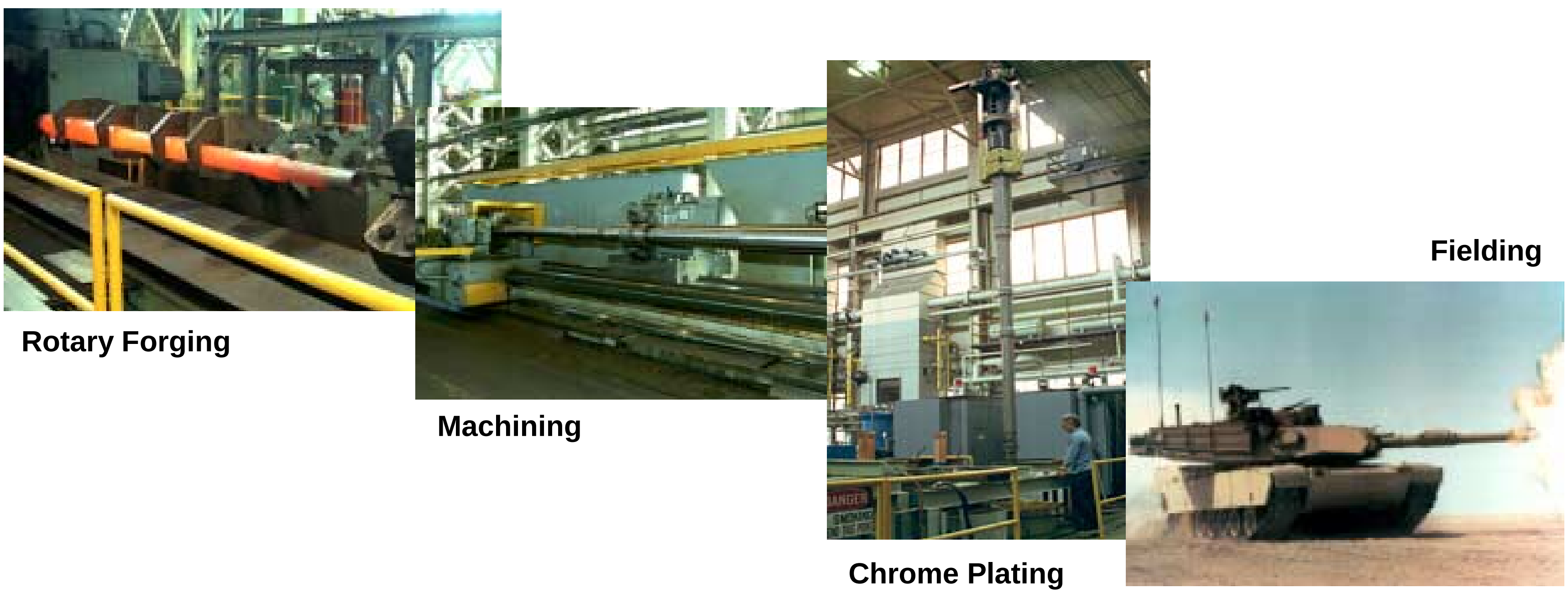


CMS Process
Plasma
(Ionized Inert Gas)
I
e-
I
e-
COLLISION
e
Ar
Ar+
e-
I
I
Ta
Substrate
(Gun Tube)
Plasma
Power
Supply
+
-
I
Magnetic
Field Lines, B
Target
Power
Supply
+
-
Target
(Cathode)
I
I

Figure 4

LARGE CALIBER GUN BARREL MANUFACTURING PROCESS





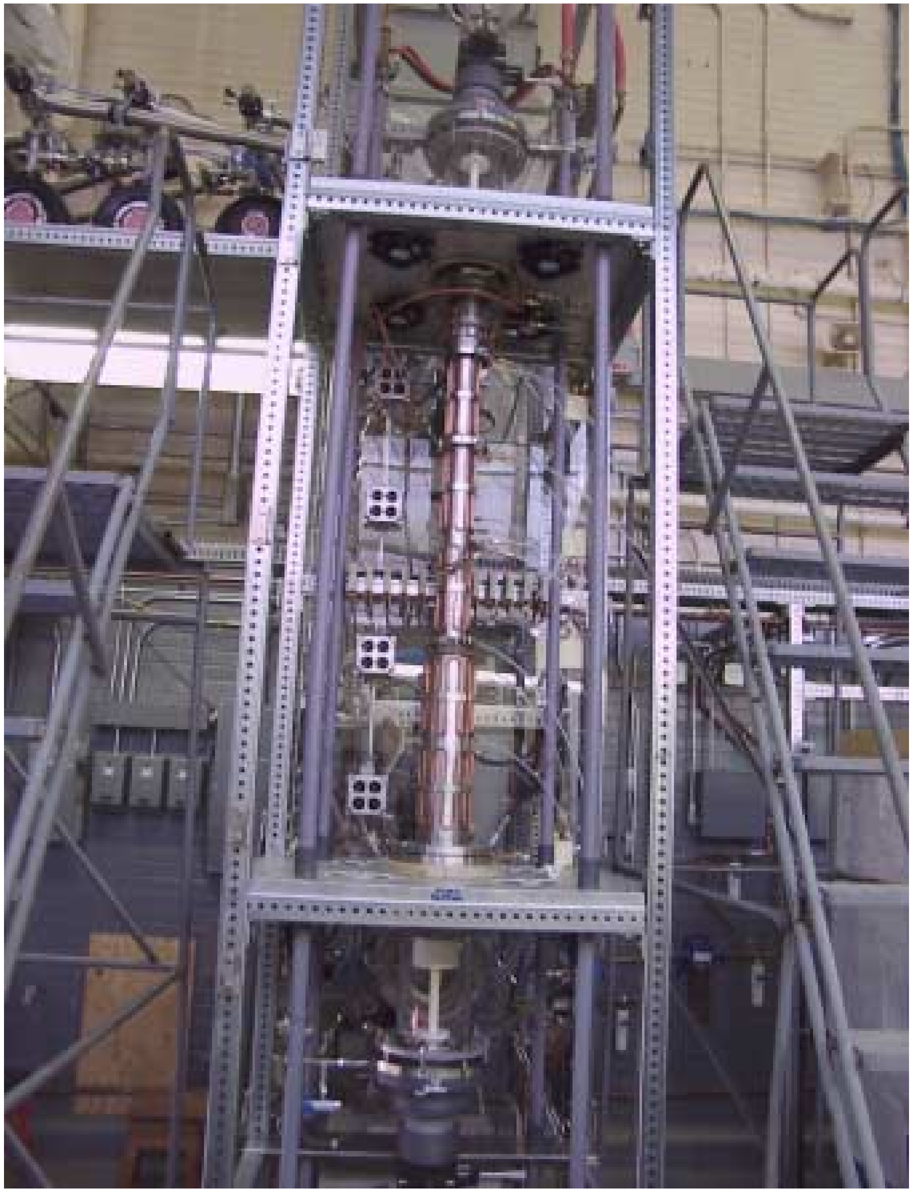
Rotary Forging

Machining

Chrome Plating

Fielding

Figure 5



FLOW CHART
CMS COATINGS CHARACTERIZATION PROTOCOL

From Protocol V. 1.7 Last updated 5/01

Figure 6

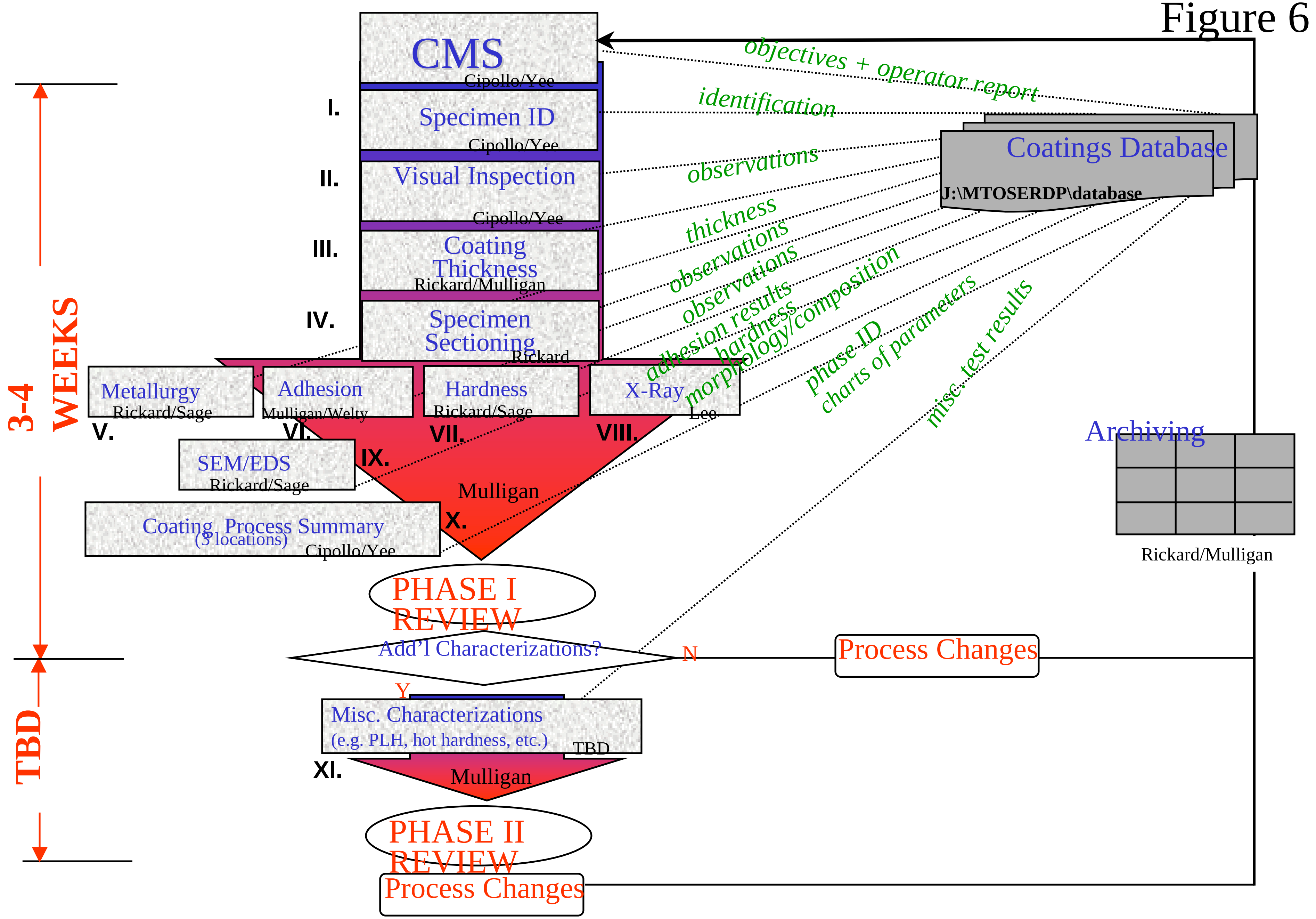
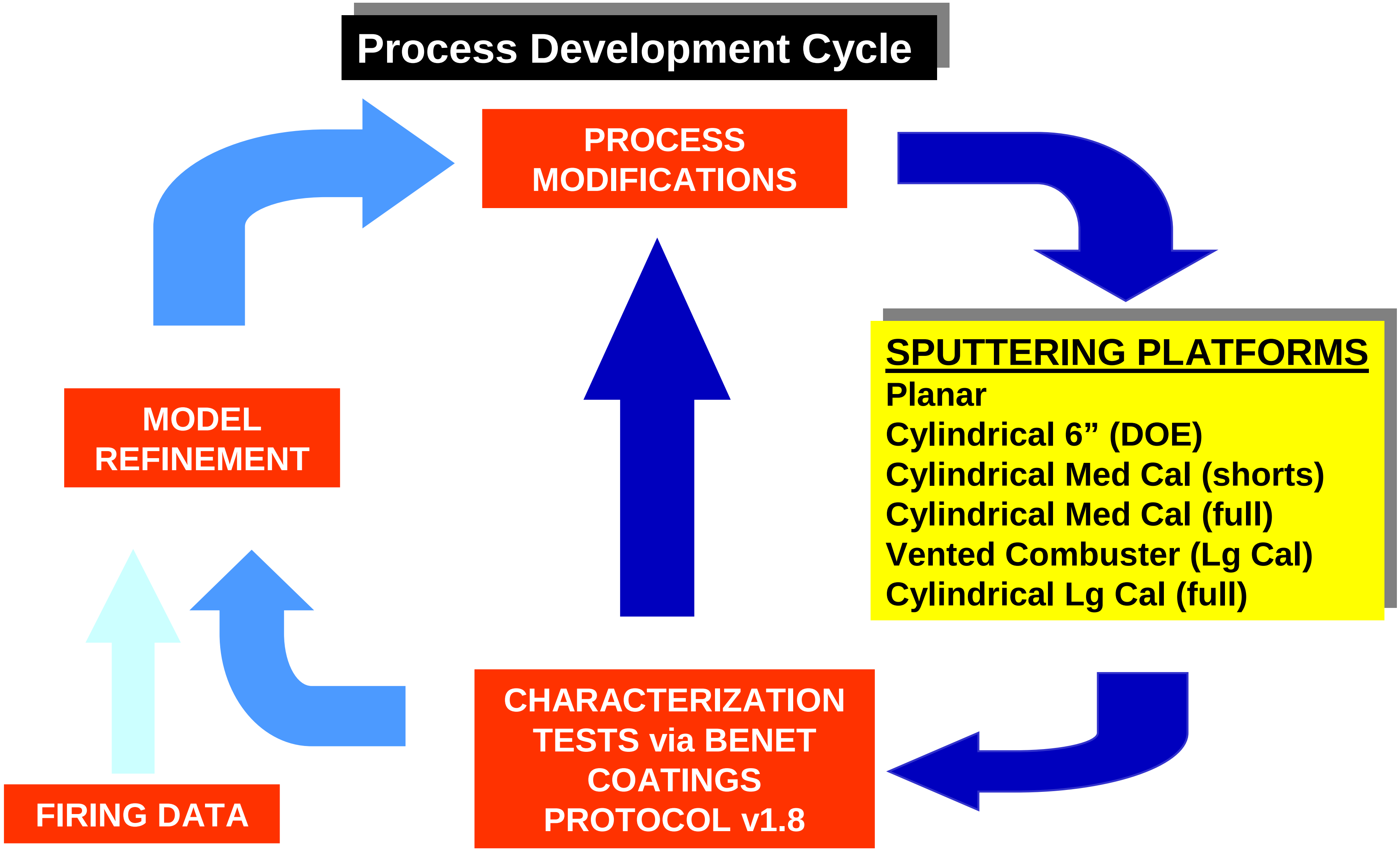


Figure 7



Process Development Cycle
PROCESS MODIFICATIONS
SPUTTERING PLATFORMS
Planar
Cylindrical 6” (DOE)
Cylindrical Med Cal (shorts)
Cylindrical Med Cal (full)
Vented Combuster (Lg Cal)
Cylindrical Lg Cal (full)
MODEL REFINEMENT
CHARACTERIZATION TESTS via BENET COATINGS PROTOCOL v1.8
FIRING DATA

Figure 8

FTMA-676

FTMA-677

Figure 9

45-mm Tube Geometry

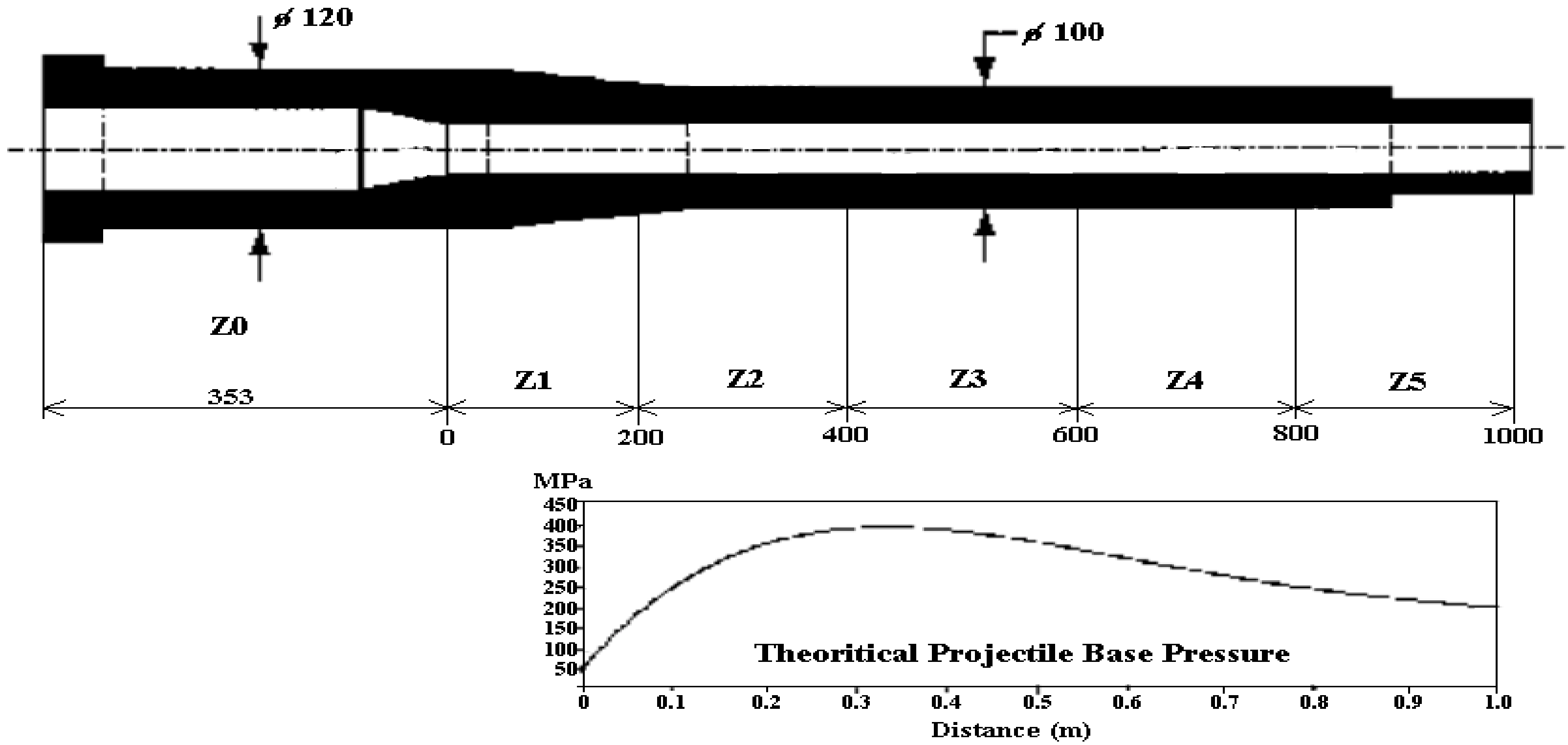


Figure 10

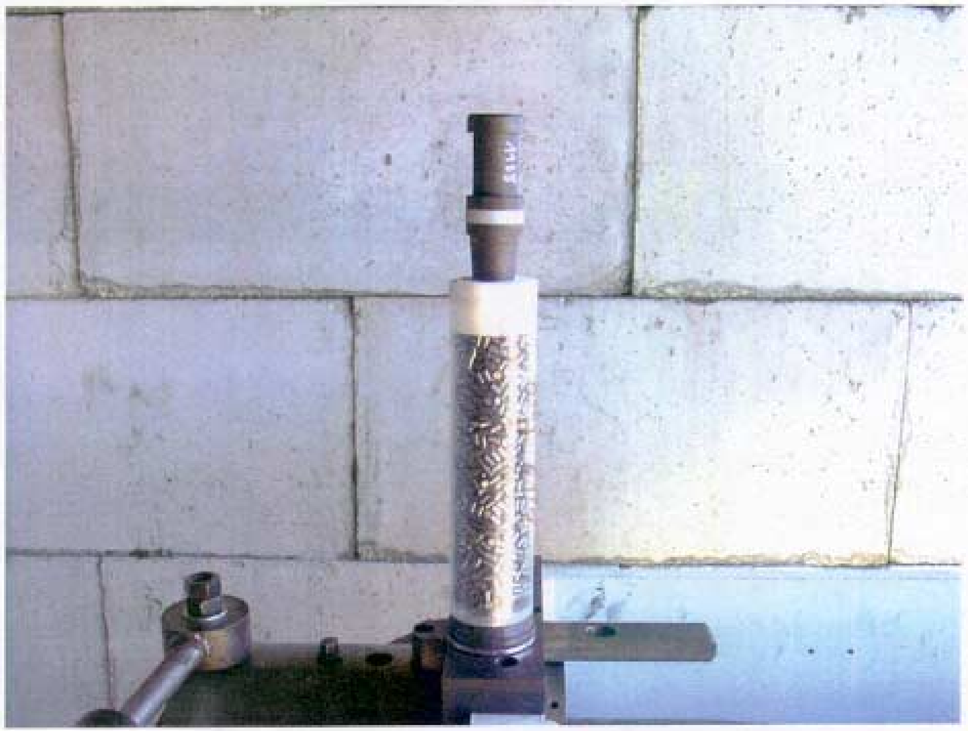


Figure 11

MEDIUM CALIBER COATINGS

CASIUS POST-FIRING RESULTS

Tube 35305

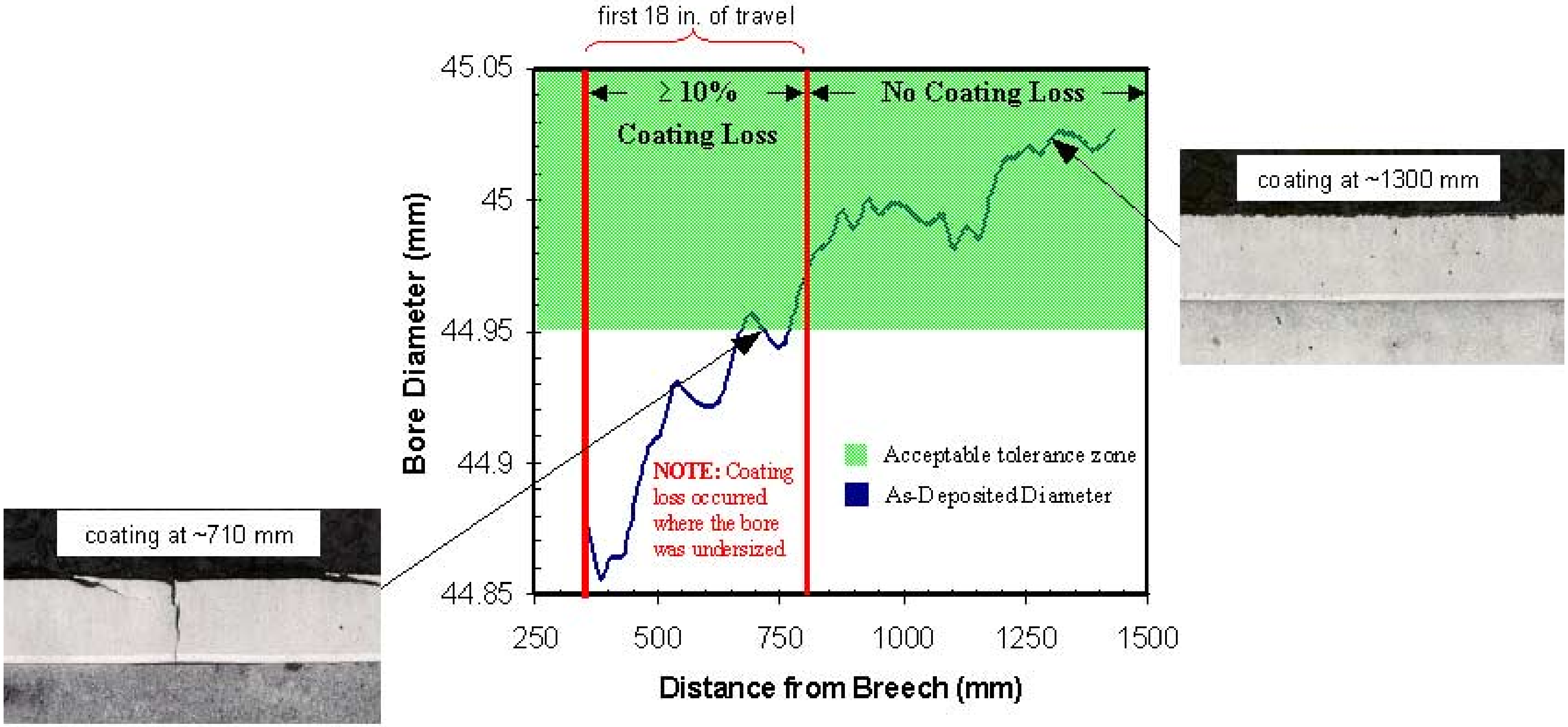
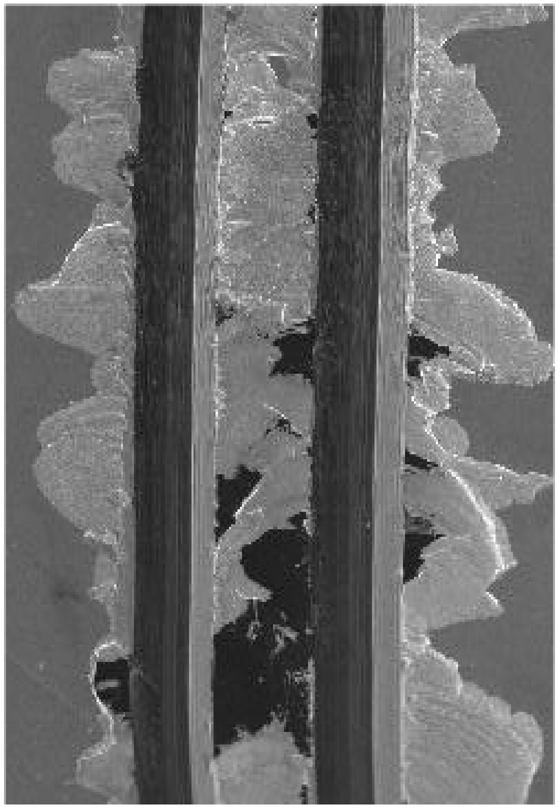


Figure 12

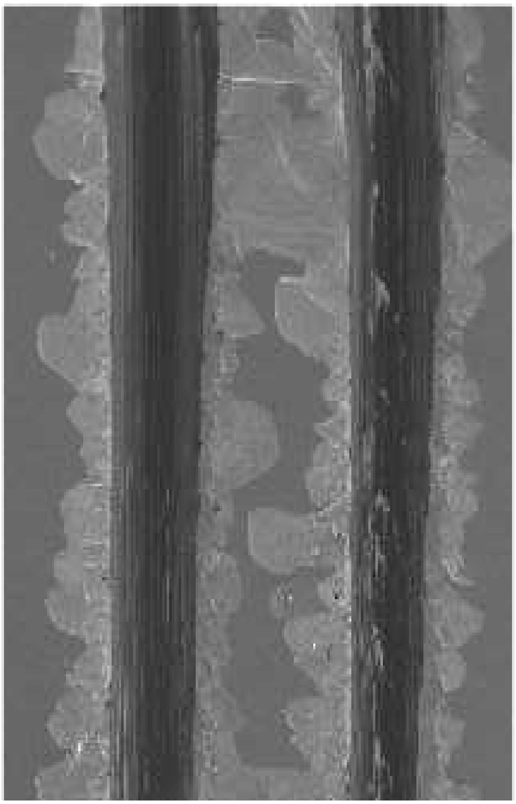
COATING ADHESION TESTING

Groove Testing

HC Chrome – good adhesion



Beta-Ta – poor adhesion



Beta-Ta – good adhesion
SN 35302

Figure 13

HAZ

SN 35302 / Zone 2

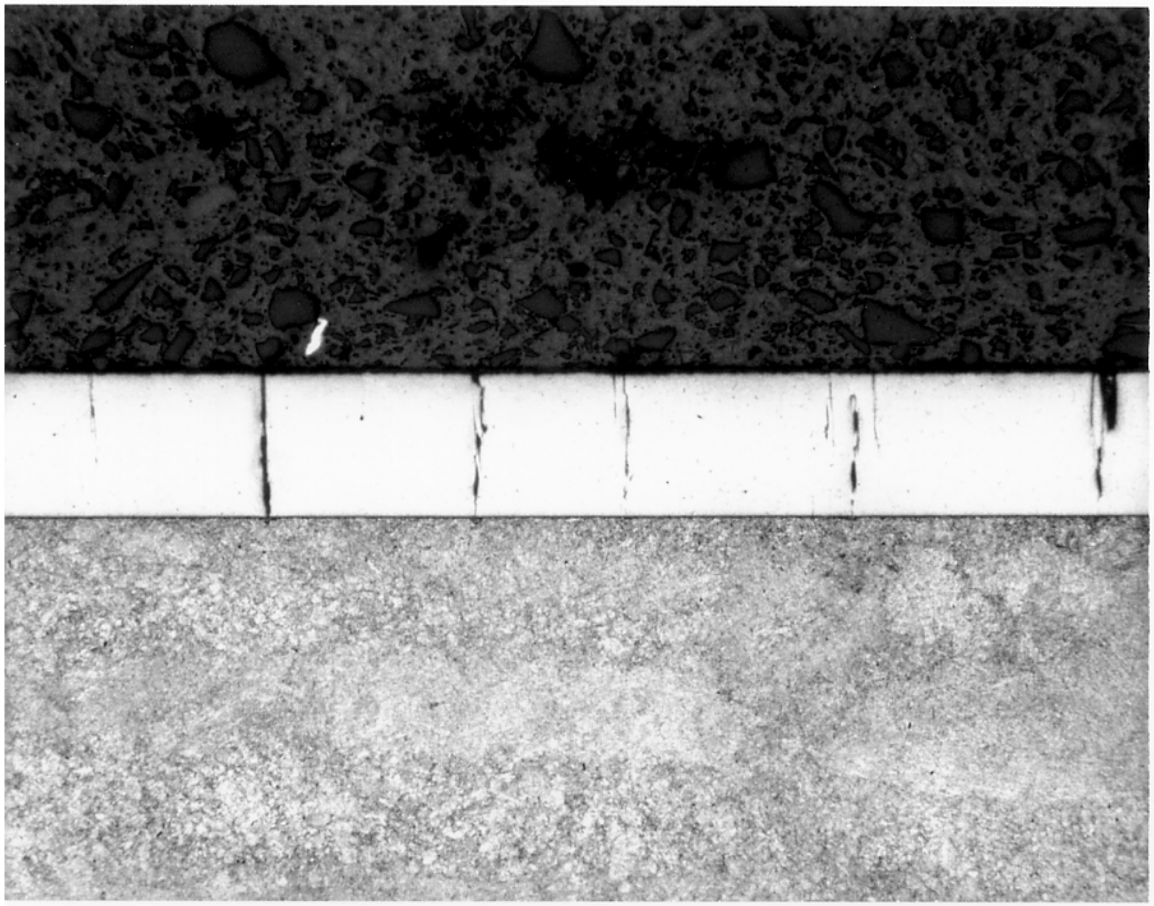


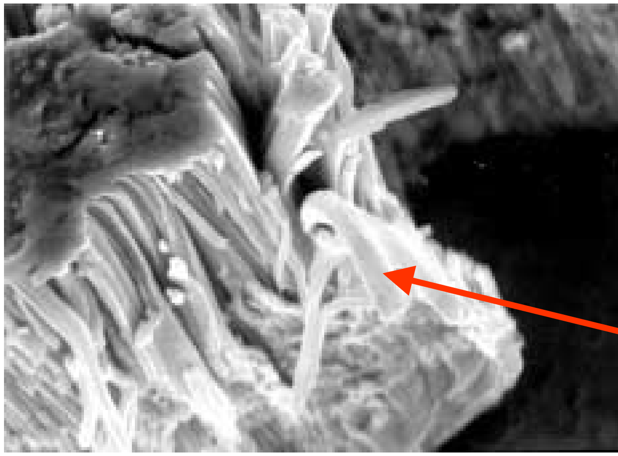
Figure 14

Crack Density Levels – SN35302

		Fired Specimen Barrel Sample Reference Number: 35302	
		Barrel Axis Direction (crack/mm)	Radial Direction (crack/mm)
Large Crack	Zone 1	3.4	- -
Micro-Crack		3.2	- -
Large Crack	Zone 2	4.6	3.2
Micro-Crack		3.0	3.0
Large Crack	Zone 3	2.4	0.0
Micro-Crack		5.6	2.4
Large Crack	Zone 4	2.4	0.2
Micro-Crack		8.2	11.0
Large Crack	Zone 5	4.6	0.8
Micro-Crack		10.0	10.0

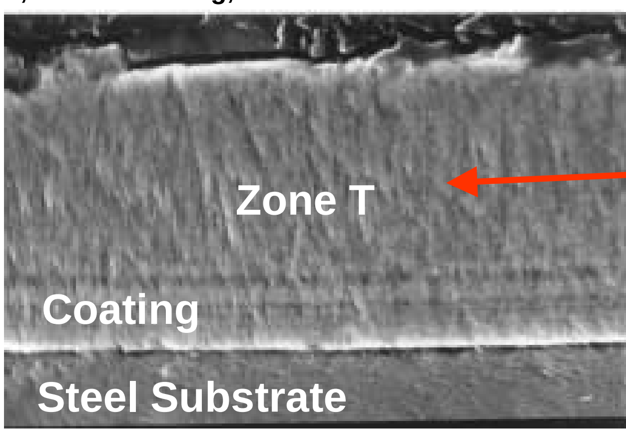
Figure 15

Columnar, porous coating w/poor lateral strength



Less Dense Coating

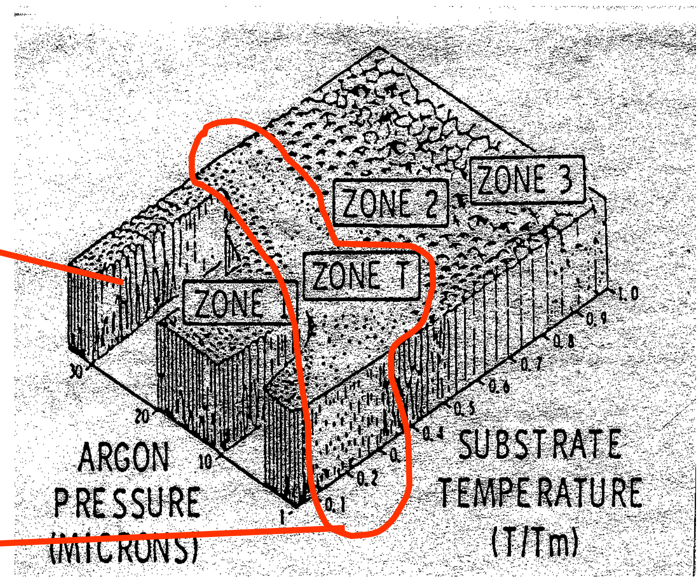
Dense, fibrous coating, excellent adhesion/cohesion & lateral strength



More Dense Coating

COATING MORPHOLOGY
Thornton Diagram

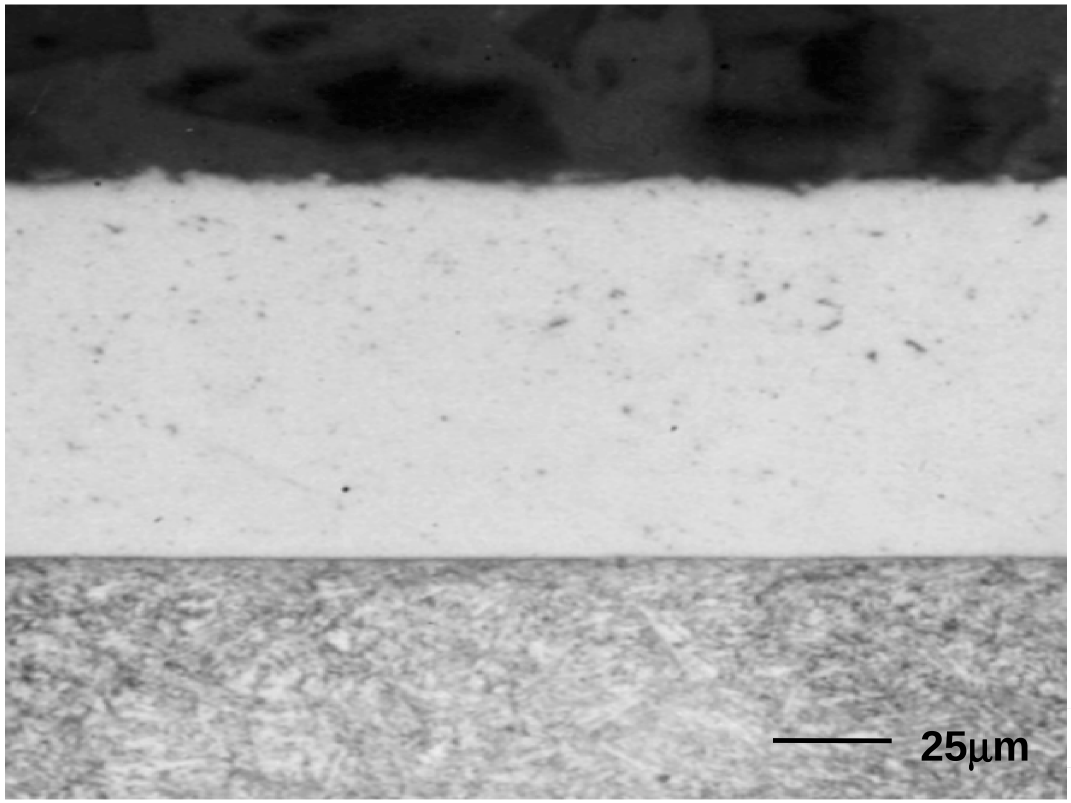
- **Zone T Structure – The desired morphology for Benet CMS coatings**



J.A.Thornton, Journal of Vacuum Technology, Vol 11, pg 666, 1974

Figure 16

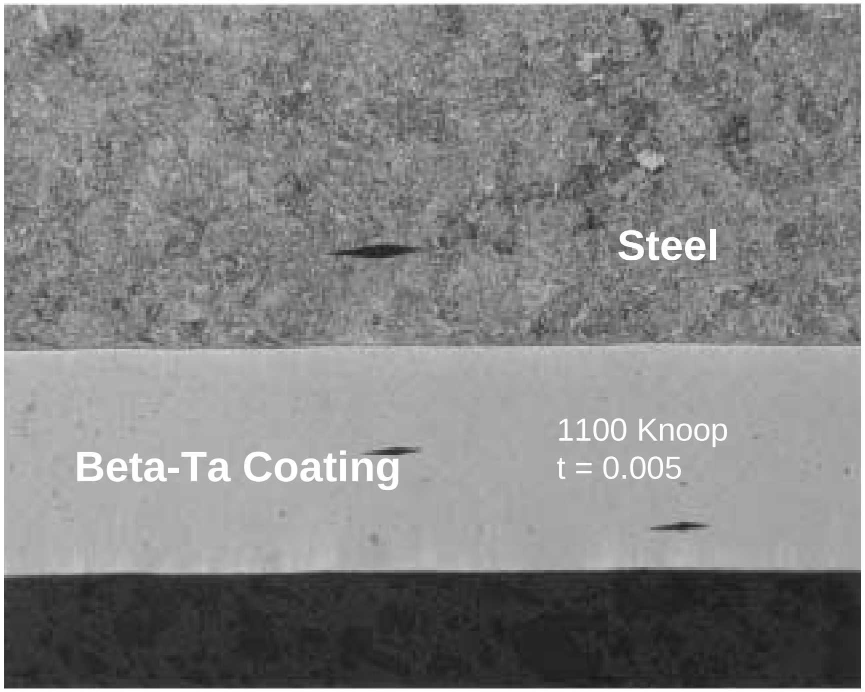
Promotion of 100% α Ta w/o Interlayer or Seed Layer



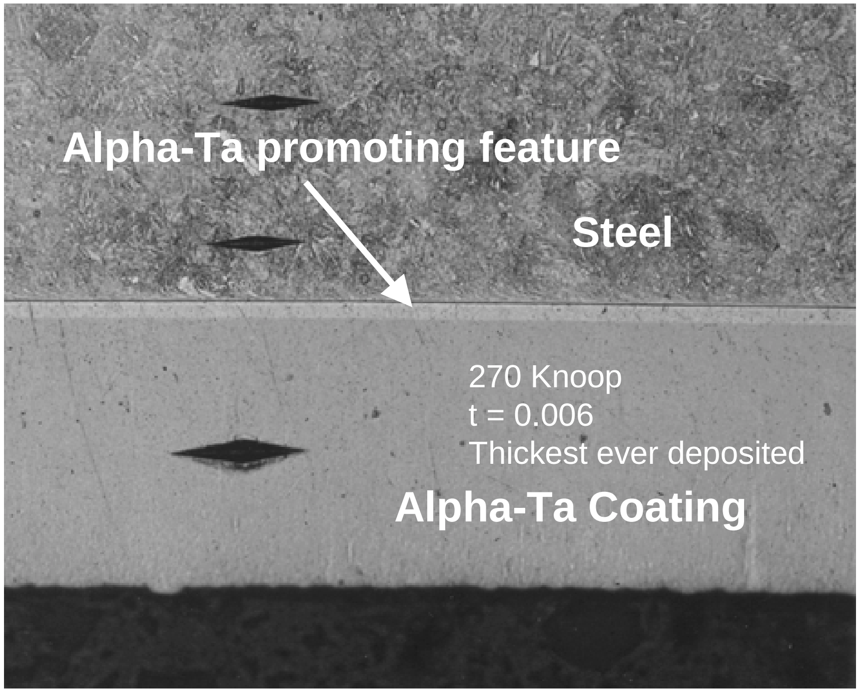
Higher T, lower P, and improved cleanliness promoted 100% α Ta

Figure 17

Past Depositions



Recent Deposition

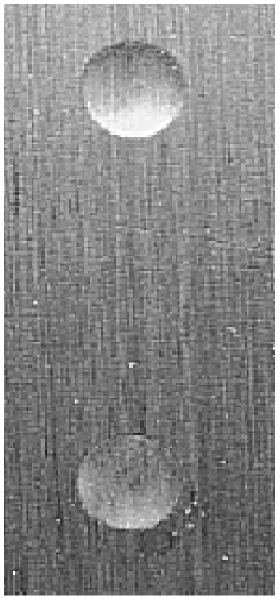


Reference:	Cr Plating after deposition:	900 Knoop
	Cr Plating after firing:	200-300 Knoop

Figure 18

COATING ADHESION TESTING

Dimple and Groove Testing



Chrome Plating on Gun Steel via Aqueous Electrodeposition

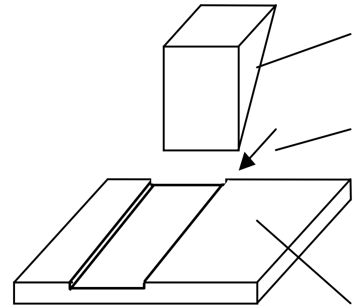
EXCELLENT ADHESION

Tantalum on Gun Steel via Cylindrical Magnetron Sputtering

POOR ADHESION Circa 1999

Tantalum on Gun Steel via Cylindrical Magnetron Sputtering

EXCELLENT ADHESION Circa 2001



No Adhesive Failure

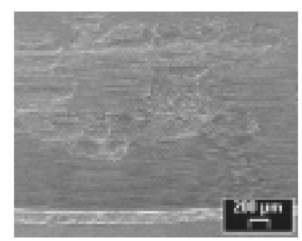


Figure 19

Results of Non-Uniform Plasma Cleaning

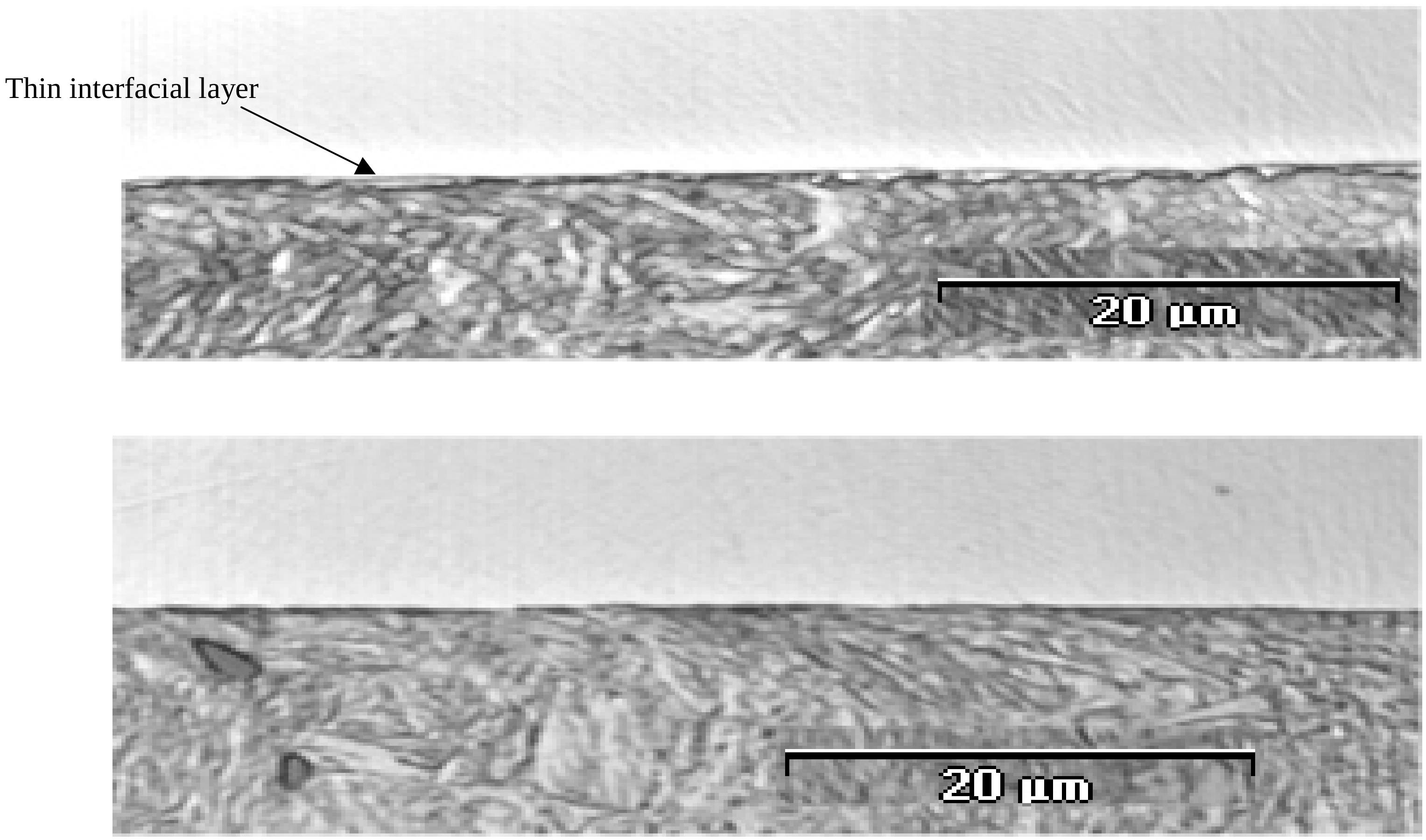
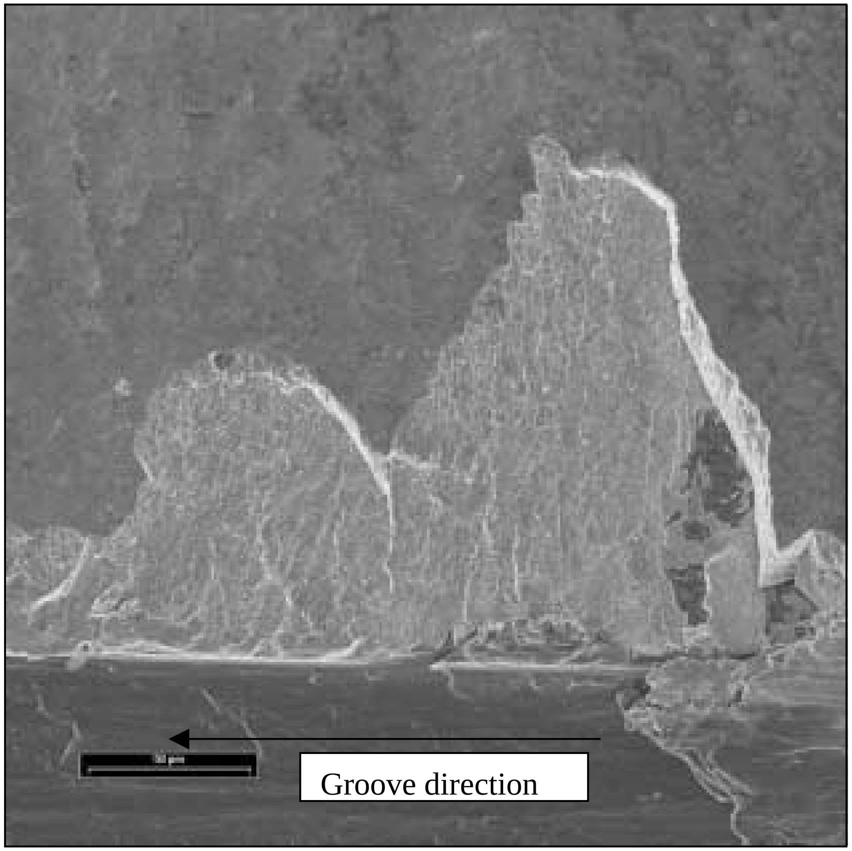


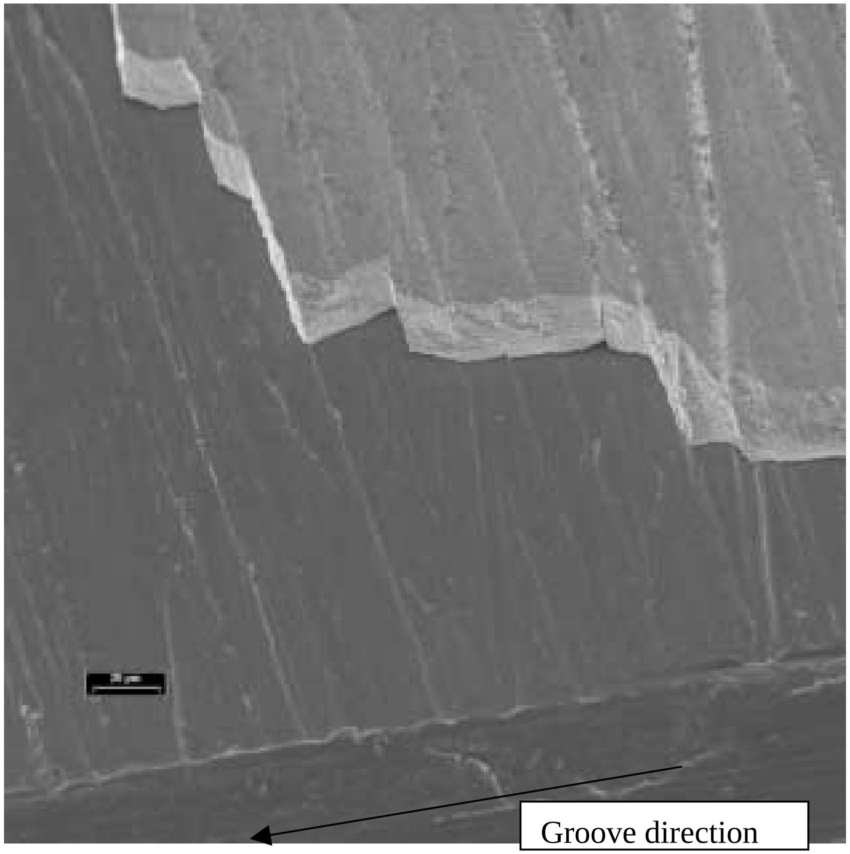
Figure 20

Typical Results of Non-Uniform Plasma Cleaning

Good adhesion, no clear-cut signs of adhesive failure

Poor adhesion, same sample, 180° away.



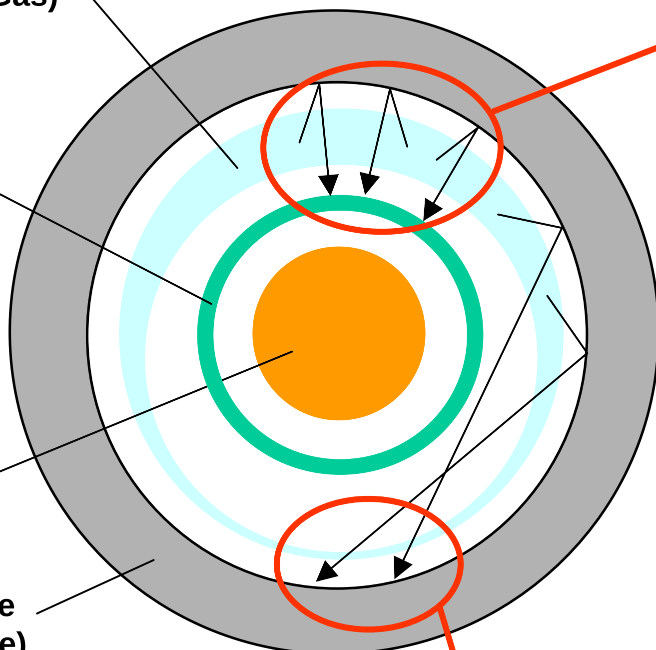


Medium Caliber

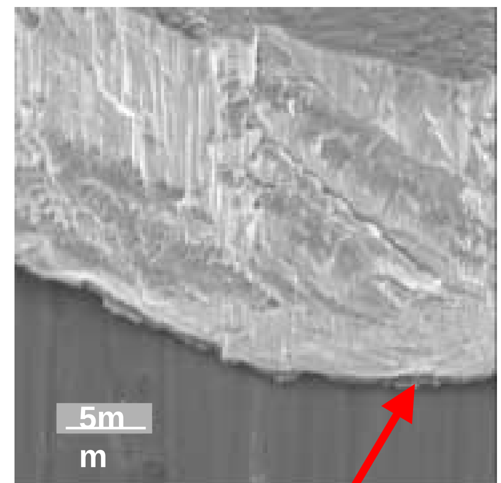
Figure 21

COATING ADHESION CHALLENGES

Non-Concentric Plasma Cleaning



“Sputter-Cleaning correctly depositing surface contaminants onto removable shield



Re-Deposited Fe Layer

Surface contaminants missing removable shield and re-depositing onto barrel.
Contaminant deposition rate exceeds cleaning rate thus contaminants stay on barrel.

Figure 22

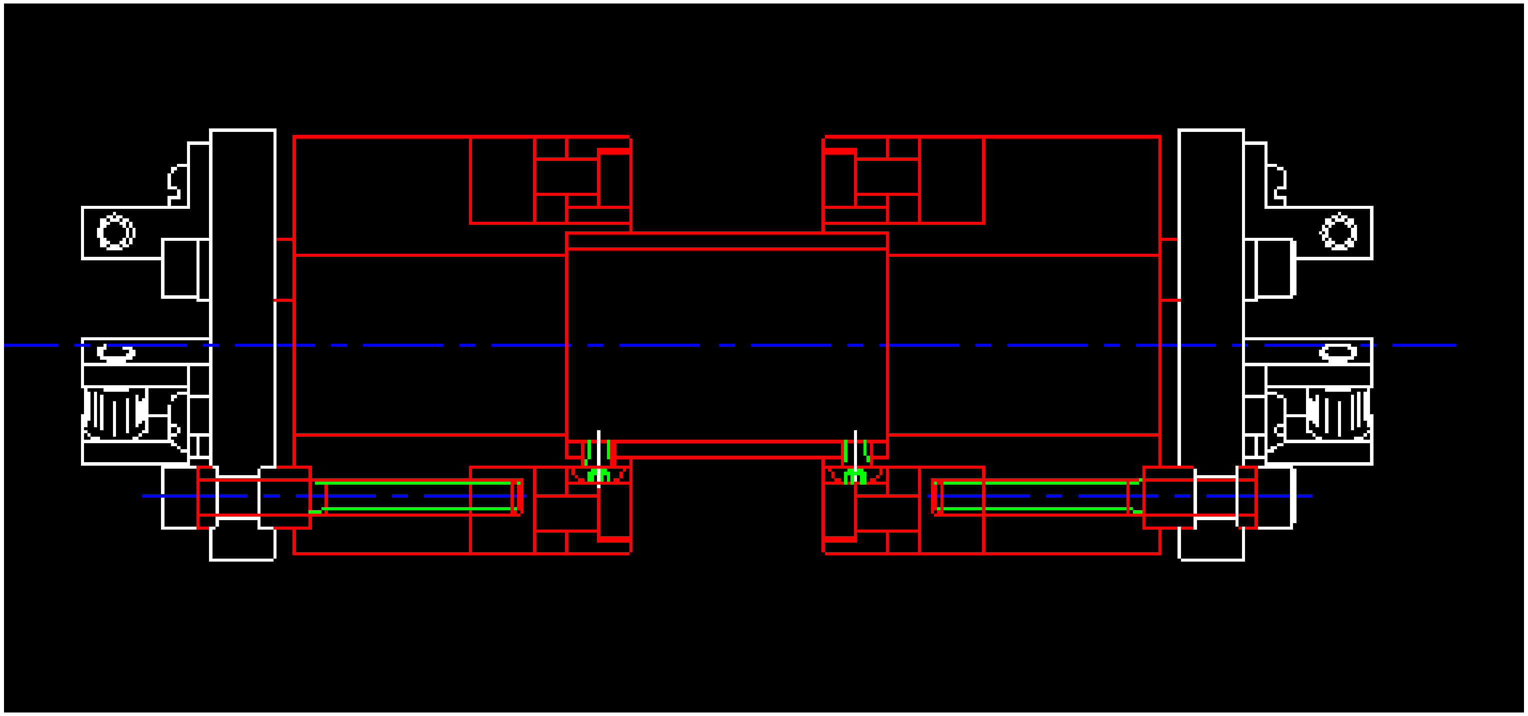


Figure 23

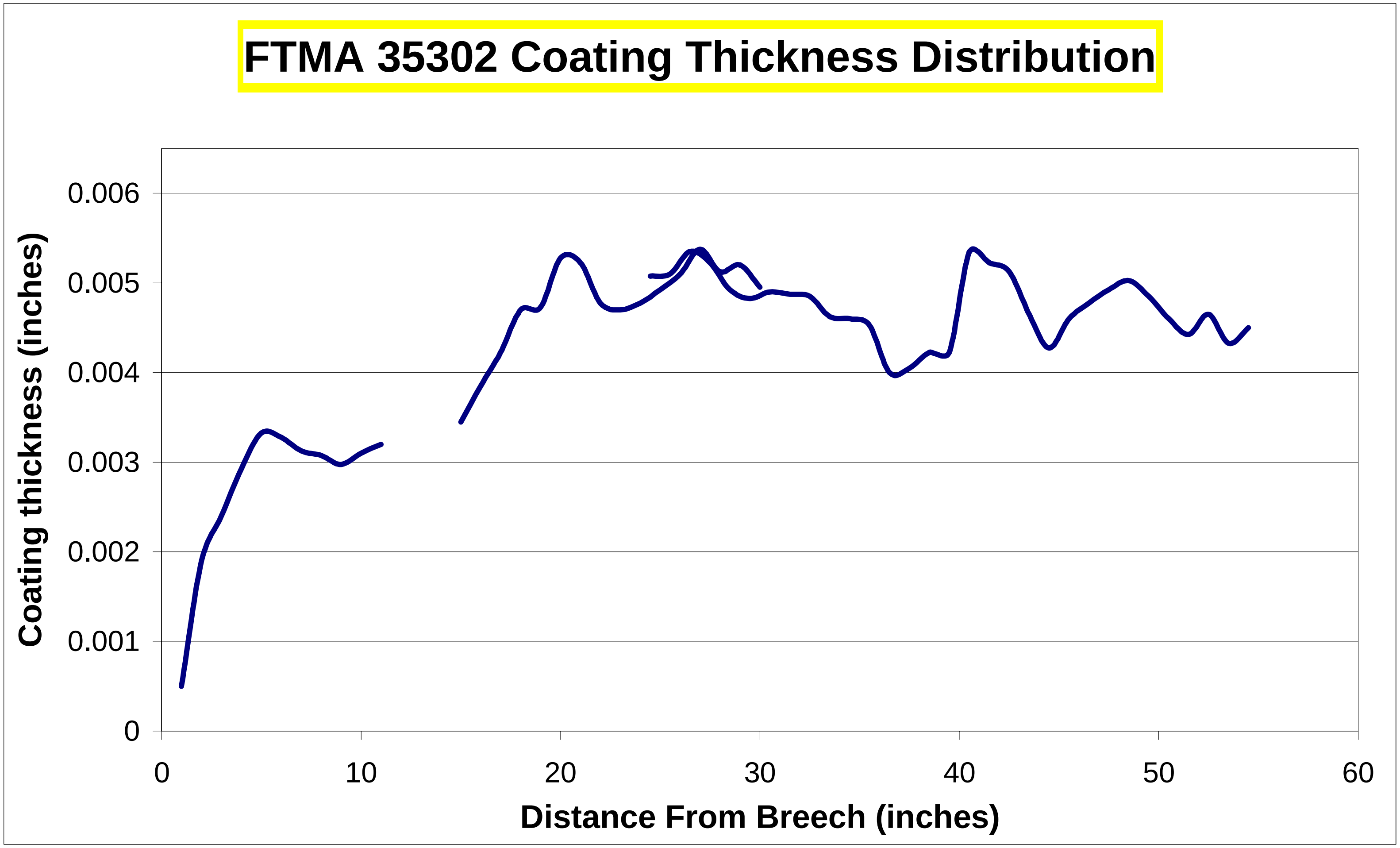
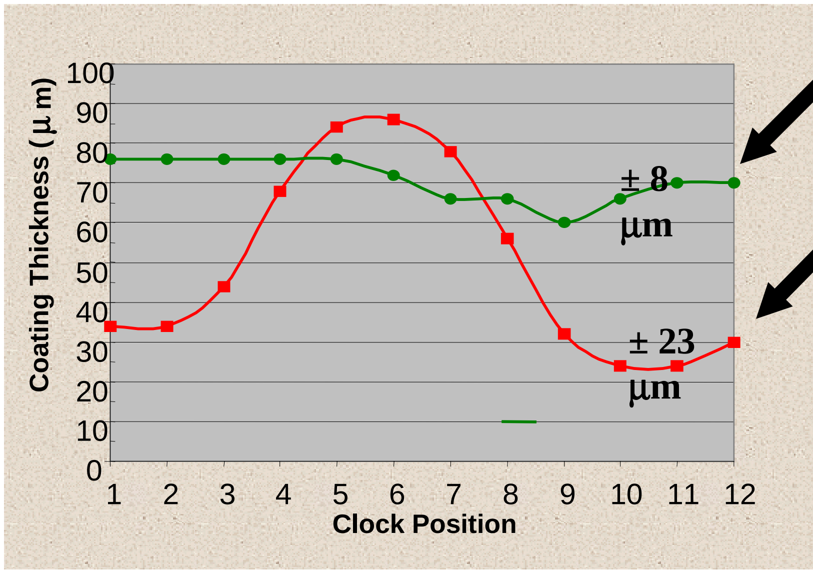

FTMA 35302 Coating Thickness Distribution
Coating thickness (inches)
0.006
0.005
0.004
0.003
0.002
0.001
0
0
10
20
30
40
50
60
Distance From Breech (inches)

Figure 24



Circumferential coating distribution using modified target design for first time

Typical circumferential coating deposition using prior methods in generating the required ionization

Typical circumferential distributions utilizing target design modification and increased ionization efficiencies